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RAPID CALCULATION OF THREE-DIMENSIONAL FLOWS IN FLUSH INLETS.(U)
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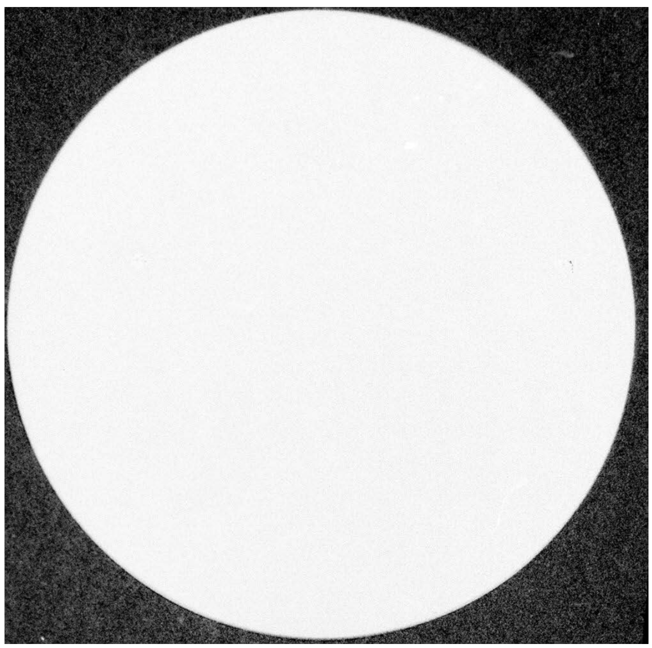

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~~ONR CONTRACT N00014-76-C-0324~~

6 RAPID CALCULATION OF THREE-DIMENSIONAL FLOWS IN FLUSH INLETS.

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by

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Date Submitted: 11 31 Marc[redacted]79

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FINAL REPORT ON ONR CONTRACT N00014-76-C-0324,
"RAPID CALCULATION OF THREE DIMENSIONAL FLOWS IN FLUSH INLETS"

SUMMARY

The development of semidirect methods for rapidly calculating steady-state viscous flows in channels is described. The methods successfully calculate laminar flows in almost arbitrary two-dimensional channels, and also work successfully for turbulent flows. The methods are not successful in three dimensions.

INTRODUCTION

The water inlets for ships powered by reaction jets (water pumps) are often mounted essentially flush to the hull, below the water line. The inlet geometry is variable in order to regulate the mass flow rate over a wide range of operating conditions, from start-up to high speed. The accurate and rapid calculation of flows in flush inlets is of interest for the prediction of the total drag of the ship and the performance of the pump.

The proposal for the subject contract was to develop a computer code, based on semidirect numerical methods, for the rapid calculation of the steady-state flows in flush inlets using the full incompressible Navier-Stokes equations. In these semidirect methods, the nonlinear Navier-Stokes equations are solved by non-time-like iterations; in each iteration, a linearized set of equations is solved directly (i.e., non-iteratively) using a fast linear elliptic solver. In the present case, the semidirect method used is the Split NOS method, previously developed by the Principal Investigator. It requires first-derivative (advection) terms in the linear operator, necessitating the use of the EVP method, also previously developed by the P.I., as the fast linear elliptic solver.

2D LAMINAR FLOW

The problem for two-dimensional laminar flow in a flush inlet was formulated in stream function (ψ) and vorticity (ζ) variables. The channel walls were mapped onto a regular rectangular region using a linear stretching

in the y-coordinate. This non-orthogonal transformation allows for arbitrary specification of the shape of the upper and lower surfaces, either by analytic function or tabular input, except that double-valued functions are not allowed (i.e., a wall which turns back onto itself). Since the walls are not normal to the y-coordinate, the slope of each wall is required in the evaluation of wall vorticity and the transformation coefficients. These derivatives are obtained numerically by finite differences up to $O(\Delta^6)$ accurate. The interpolation required for wall vorticity is carried out so as to maintain second-order accuracy. A non-conservation form of the vorticity transport equation is used, since this simplifies the transformed equations.

The non-orthogonal transformation introduces cross-derivatives like $\partial^2(\ )/\partial x \partial y$ into the governing flow equations. The EVP method for the direct solution of linear elliptic equations was extended to include these variable coefficient cross-derivative terms in both the Poisson equation for stream function and in the linearized vorticity transport equation, which also includes variable-coefficient first-derivative (advection) terms. The operation count for the EVP method with cross-derivatives was obtained. The presence of a simple cross-derivative term requires a tridiagonal solution at each line in the march solution and increases the operation count by a factor of 2 for the initial solution and by a factor of 2½ for repeat solutions, compared to the simple Poisson equation. Many other aspects of the marching methods were improved and refined during the contract period.

The outflow boundary conditions used are compatible with the conditions used in time-dependent methods; they are a gradient-type condition on vorticity (ζ) and an even less restrictive condition on the second spatial derivative $\partial^2\psi/\partial x^2$. Because of the non-orthogonal transformation, an additional assumption on $\partial^2\psi/\partial x \partial y$ is required at outflow; the results are entirely satisfactory provided that the channel at outflow is constant or converging; if the channel is diverging, the upstream results are excessively sensitive to outflow conditions, as is the case with time-like methods.

Any discrete solutions of the Navier-Stokes equations, either by finite difference methods of finite element methods, will have accuracy

limitations at high Reynolds number Re, depending on the flow gradients and the mesh spacing. Within these universal limitations on accuracy, the presently developed semidirect methods have displayed no Re limitations on convergence. Although iterative convergence is slower at high Re (but still much better than time-dependent methods) this can be alleviated by "stacking" Re cases. This option is built into the codes, and allows the results from a previous (lower) Re solution to be used as the initial guess for the higher Re iterations. Weakly separated flows have been successfully calculated at $Re = 10^7$. The laminar two-dimensional channel problem, with almost arbitrary lower wall shape, restricted only by the accuracy conditions to weak separation, is now considered to be essentially solved. For fairly large problems (51x51), complete solutions are typically obtained in $\sim$15 msec/cell on a CDC 6600. These methods are used in the code CHLG.

2D TURBULENT FLOW

Turbulence models in many and varied forms are now available. All introduce variable-coefficient diffusion terms into the vorticity transport equation. The EVP direct elliptic solver was extended to treat the variable coefficient turbulent diffusion terms. A program to solve the turbulent flow problem in rectangular (non-transformed) coordinates was written using this version of the EVP solver and a simple channel form for the turbulent stresses, $\varepsilon = \ell^2 y^2 |\zeta|$. The increased ellipticity of the eddy viscosity terms in the y-direction considerably aids the error propagation characteristics of the EVP method. Combined with the fact that the operation count for the EVP method is much more sensitive to the number of points in the x-direction than in the y-direction, this makes it feasible to compute directly into the sublayer using an additional coordinate stretching in y. The two-dimensional turbulent channel-flow code CHTS exhibits no Re limitations on stability. It still remains to incorporate the turbulence terms into the general channel code allowing for arbitrary upper and lower wall shapes.

A one-dimensional code for a turbulent Burgers equation was used to study the convergence of the turbulence equations at high Re and to enhance

iterative convergence. The techniques tested include Aitken, Martin-Aitken, and Milne extrapolations. The coupling between the ψ and ζ equations occurs in two ways, nonlinearly through the advection terms and the turbulent diffusion terms, and linearly through the boundary condition on ζ at a no-slip wall. It is the latter coupling that necessitates under-relaxation of ζ at a no-slip wall. In previous work, the optimum under-relaxation factor r was determined analytically only for the simplest one-dimensional flows without advection, Couette flow and Poisseuille flow. It was determined that iteration of the linearized one-dimensional problems (including linearized advection and turbulent viscosity terms) results in a sequence of wall vorticity values which is geometric; i.e., the ratio of successive differences is constant. Thus for the linear problem, after the first three iterations from an arbitrary initial condition, Aitken extrapolation yields the exact answer for wall vorticity, and the total linear problem is solved exactly on the fourth iteration. For the nonlinear problems of interest, if the initial condition is reasonable, the Aitken extrapolation gives a good estimate of the final wall vorticity, so the number of (nonlinear) iterations is reduced. However, the most significant aspect is that this extrapolation can then be used to determine the exact optimum under-relaxation factor, which gives exact iterative convergence of the linearized equation in one step from an arbitrary initial guess, and which produces the most rapid iterative convergence for the nonlinear equations. Unfortunately, the sequence of wall vorticities for the two-dimensional problems is not so well-behaved, and a set of exactly optimum under-relaxation parameters is not possible in two-dimensions. (Such a set would turn any Poisson solver into a biharmonic solver, for example.) However, the one-dimensional technique has been used to considerable advantage in the two-dimensional channel flow problems of interest to predict the effect of turbulence terms, boundary conditions, v-advection terms, Reynolds number, and mesh size on the optimum r. In a subroutine, it can be used to give a practical estimate of the optimum r for these two-dimensional problems.

A new approach to the expanding mesh construction for turbulent boundary layers was tested. The mesh construction is based on the Fibonacci sequence, and allows 3-point second-order differences to be used in a rapidly

expanding mesh which is appropriate for turbulence calculations. We verified convergence of the solution, and learned how to implement the mesh in a semidirect solution. However, we have not been able to compare this new approach with conventional expanding-mesh schemes.

Originally, we proposed to incorporate a 2-equation turbulence model in our work. We re-evaluated the originally-proposed method for treating the turbulence. Our study of the currently available methods has been corroborated by discussions with several researchers active in turbulence modeling. For simple one-dimensional test problems, all the theories work if the correct wall values are given, but no theory is really complete for the separated flow cases of interest. It was decided to perform the separated flow turbulence modeling based on engineering extensions of the simple mixing-length models for the present time, since the performance and incompleteness of the more elaborate models did not seem to justify further investment of effort.

3D LINEAR SOLUTIONS

One of the most successful aspects of the present contract work was the development of a three-dimensional direct linear solver, the 3D EVP/FFT method. This is a combination of Hockney's method with our previously developed EVP method. The dependent variable is first Fourier transformed in the third coordinate (channel width) using the Fast Fourier Transform. Then the EVP method is used to solve the two-dimensional problem in x and y for each Fourier component, followed by a reverse transformation. The operation count for this method for an IxJxK problem is $O(I \cdot J \cdot K \cdot \ell n K)$. Although the Fourier-transformed variable is complex, the required influence coefficient matrix is real. Further, it is symmetric in the wave number, thus reducing the required storage and operation count by almost a factor of one half. The error propagation characteristics were worked out in detail for this 3D method, and it was shown to be applicable to the geometries of interest. This 3D solver retains the ability of the 2D EVP method to treat variable-coefficient first- and cross-derivatives in the x-y plane, although it is restricted to constant-coefficient second-derivatives in z, as are the

more common methods. In addition to the application to the three-dimensional viscous flows in the present contract, it appears that this 3D solver would be of interest to other naval flow problems such as 3D free surface flows.

Under separate funding, a simple 3D marching method was also developed, but is limited to coarse-mesh solutions (see below).

3D NONLINEAR SOLUTIONS

The major effort of the coding of the 3D nonlinear solution and the subsequent testing was completed, with uniformly negative results.

The 3D EVP/FFT method was coded into a CALLable subroutine and used as the basis of a fully 3D fluid dynamics solution using the vorticity-velocity variables. Extensive experimentation was carried out with this code and with a related 3D code (developed under separate funding) using the pressure-velocity variables. With both codes, tests were conducted on the simple problem of perturbed 3D Couette flow.

It appears that the 3D EVP/FFT method will not be useable for 3D fluid dynamics solutions using semidirect methods. Instability resulted at all non-zero Reynolds numbers in both codes, using a variety of boundary conditions. With only a decoupled transport equation active, and with fixed boundary conditions, stable solutions were obtained only through Re = 10, with erratic convergence obtained at Re = 15. There always remains the possibility that the failure was due to coding errors, but the test for only the u-component is fairly straightforward, and correct solutions resulted when the equations were linearized. Also, the method is convergent in 2D even for high Re with the nonlinear equations. It therefore appears that the instability is inherent in the 3D solution using the 3D EVP/FFT direct solver. It is conjectured at this time that the instability is related to the sensitivity of the FFT to small disturbances.

The alternative semidirect method is to use the simple 3D marching method for the direct solver, which would allow the inclusion of advection terms in the third direction, and would be less sensitive to small disturbances than the 3D EVP/FFT method. This approach has three disadvantages.

(1) The operation count is far from optimal, especially for initialization, for $\Delta x = \Delta y$. (2) The storage penalty is high. (3) The mesh size is limited to about 16x16x16 by round-off error considerations. This could possibly be extended, with a considerable programming effort, to about 25x25x25 with variable grid spacing. However, the convergence of the nonlinear iteration scheme in 3D has not been demonstrated.

We regret that this effort has not been successful for the 3D solutions. However, we are of the opinion that the 2D solution methods developed under this contract, for variable geometry channels in laminar and turbulent flows, are a significant contribution to the state of the art in computational fluid dynamics. The two codes which embody these methods are being sent to NSRDC along with this final report. It is hoped that these codes will find application to problems in naval ship hydrodynamics.

PUBLICATIONS AND PRESENTATIONS PARTIALLY SUPPORTED BY THIS CONTRACT

Publications

"A Semidirect Method for Internal Flows in Flush Inlets," AIAA Paper 77-647, June 1977.

"Marching Methods for Elliptic Problems: Part 1," Vol. 1, No. 1, Numerical Heat Transfer, pp. 1-25.

"Marching Methods for Elliptic Problems: Part 2," Vol. 1, No. 2, Numerical Heat Transfer, pp. 163-181.

"Marching Methods for Elliptic Problems: Part 3," Vol. 1, No. 2, Numerical Heat Transfer, pp. 183-201.

"Semidirect Calculation of Steady Two- and Three-Dimensional Flows," in Numerical Methods in Laminar and Turbulent Flow, Proc. First International Conference, University College, Swansea, Wales, 17-21 July 1978. Pentech Press, London, pp. 17-28.

"Efficiency Trade-Offs on Steady-State Methods Using FEM and FDM," with D. K. Gartling, in Numerical Methods in Laminar and Turbulent Flow, Proc. First International Conference, University College, Swansea, Wales, 17-21 July 1978. Pentech Press, London, pp. 103-112.

Presentations

"Semidirect Methods for the Navier-Stokes Equations", Seminar at the University of Houston, College of Engineering, 28 January 1976.

"Direct Solution of Variable Coefficient Elliptic Equations Including First- and Cross-Derivatives", SIAM 1976 National Meeting, Chicago, 17 June 1976.

"Semidirect Methods for Laminar and Turbulent Flows Using the Navier-Stokes Equations", ICASE Seminar, NASA-Langley Research Center, February 1977.

"Semidirect Methods for the Steady-State Navier-Stokes Equations", Computation, Mathematics and Logistics Colloquium, David W. Taylor Naval Ship Research and Development Center, Bethesda, Maryland, April 1977.

"A Semidirect Method for Internal Flows in Flush Inlets", AIAA Third Computational Fluid Dynamics Conference, Albuquerque, NM, 27-29 June 1977.

"Direct Solution of Variable Coefficient Elliptic Equations in Three Dimensions", SIAM 1977 Fall Meeting, Albuquerque, NM, 1 November 1977.

"Semidirect Calculation of Steady Two and Three Dimensional Flows", International Conference on Numerical Methods in Laminar and Turbulent Flow , University College of Swansea, Wales, 17 July 1978.